Dark Photons in electron-proton collisions

[arXiv:1909.02312]

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Model

- $U(1)_X$ extension of the Standard Model gauge group:

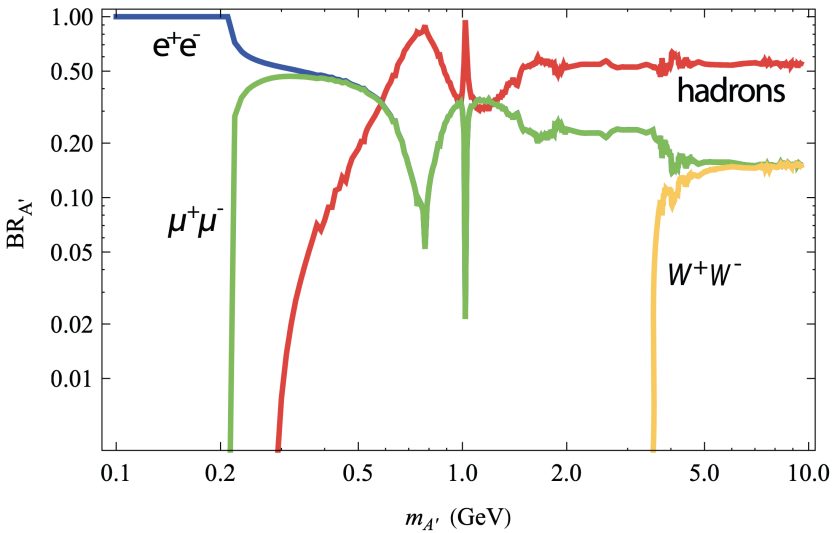
$$\mathcal{L} \supset \frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{1}{4} X_{\mu\nu} X^{\mu\nu} - \frac{\epsilon}{2} X_{\mu\nu} F^{\mu\nu}$$

- SM fermions Ψ_f are uncharged under $U(1)_X$.
- Field redefinition to remove the gauge mixing term brings:

$$\mathcal{L} \supset - \sum_f \epsilon \, e \, q_f \overline{\Psi}_f \, \gamma_\mu \Psi_f \, A'^\mu,$$

- Dark photon acquires a mass, possibly via a Higgs mechanism.
- Explicitly: `Abelian_Higgs_Model` from C. Duhr.

Lifetime



M. Raggi and V. Kozhuharov, Riv. Nuovo Cim. **38** (2015) no.10, 449.

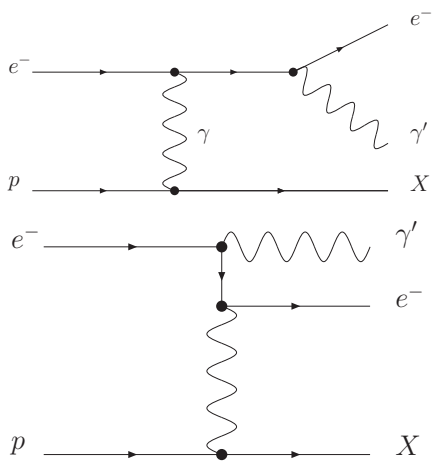
- Coupling to the electric charge defines its decay rate:

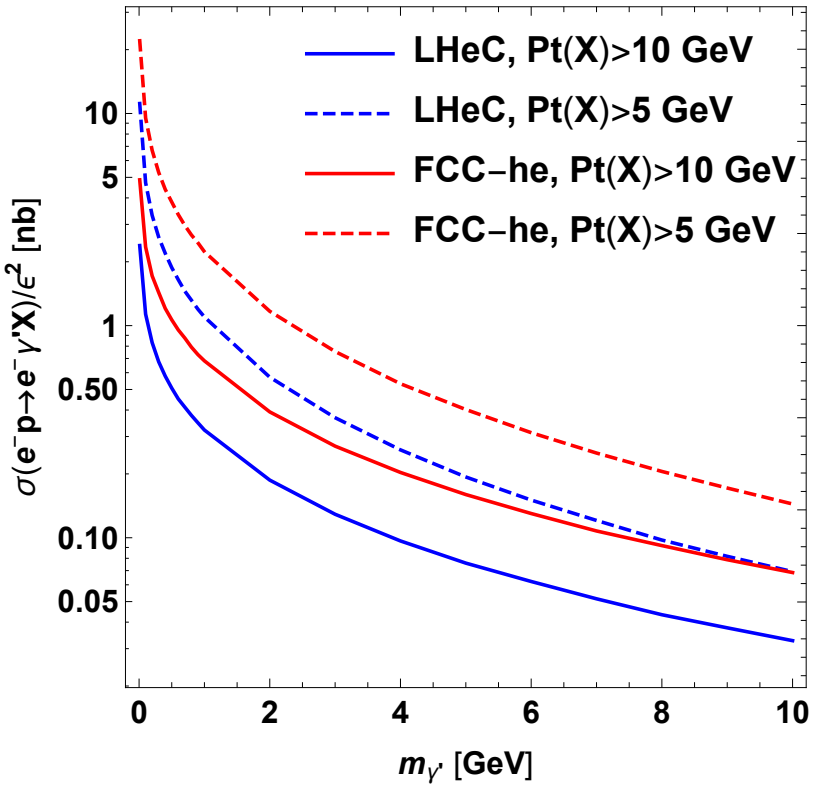
$$\Gamma(\gamma' \to l^+ l^-) = \frac{1}{3}\,\alpha_{\text{QED}}\, m_{\gamma'}\, \epsilon^2 \sqrt{1 - \frac{4m_l^2}{m_{\gamma'}^2}} \left(1 + \frac{2m_l^2}{m_{\gamma'}^2}\right),$$

- Its total decay rate can be obtained in this way:

$$\Gamma_{\text{total}}(\gamma') = \frac{\Gamma(\gamma' \to e^- e^+)}{\text{BR}(\gamma' \to e^- e^+)}.$$

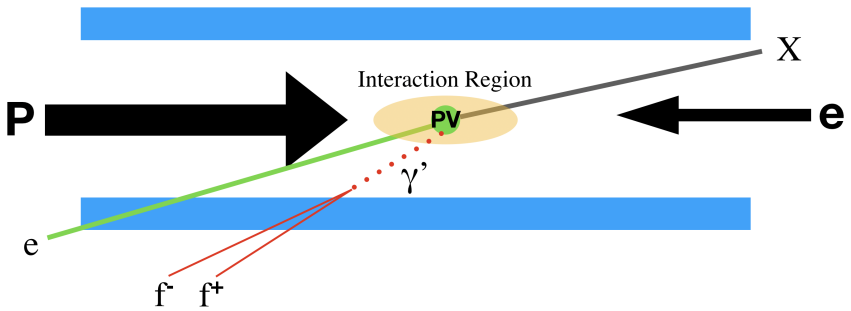
Dark photon production





- Process $e^- p \to e^- X \gamma'$, X final state hadrons
- Initial/final state radiation off the electron dominates.
  $\Rightarrow$ Process not very sensitive to proton beam parameters.
- Like QED, cross section diverges with $p_T \to 0$.
- We consider deep inelastic scattering regime: $Q^2 \gg m_p$.

Signature



- Final state $e^- X \gamma'$ with displaced decays $\gamma' \to f^+ f^-$
- $f^\pm$ are charged SM particles (read "electrons").
- All final states $|\eta| < 4.7$.
- For small momentum transfer scattering angles of the e^- and X are small compared to the respective beams.
- Primary vertex (PV) inferred from the tracks of X and e^-.
- Impact parameter resolution from CDR for vertex precision: $\mathcal{O}(10)\,\mu$m at large scattering angles to $200\,\mu$m for $\theta \sim 1°$.

LHeC Study Group, J. Phys. G **39** (2012) 075001 [arXiv:1206.2913 [physics.acc-ph]].

Displaced dark photon decays

The expected number of dark photon decays with a given displacement can be quantified with:

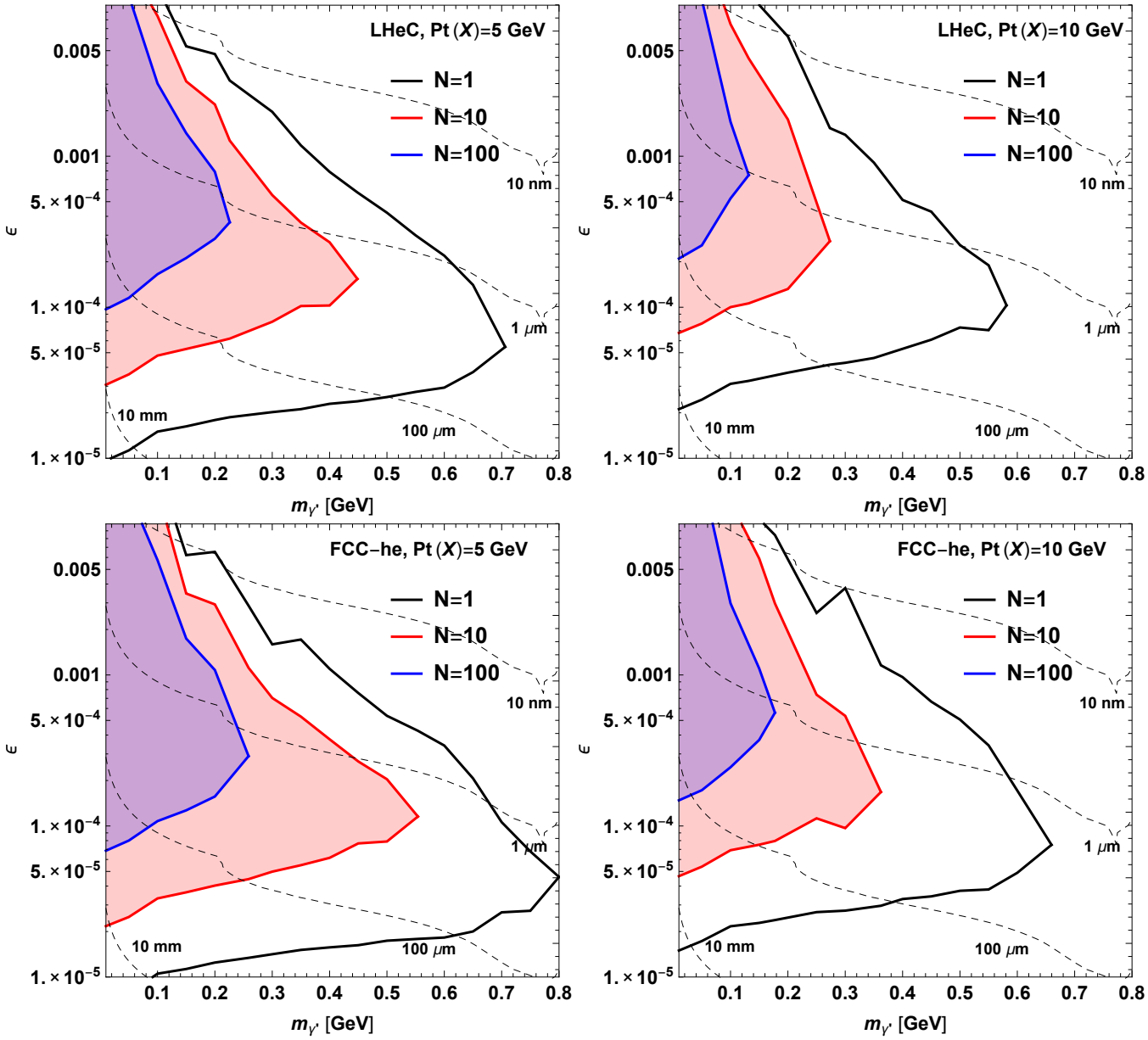
$$N_{\mathrm{dv}} = \sigma_{e^- p \to e^- X \gamma'} \, L \times \int D(\vartheta, \gamma) \, P_{\mathrm{dv}} \, d\vartheta d\gamma \, .$$

- Luminosity: $L_{\mathrm{LHeC}} = 1/\mathrm{ab}$, $L_{\mathrm{FCC-he}} = 3/\mathrm{ab}$
- The 2d distribution D from WHIZARD simulation.
- The probability of decay

$$P_{\mathrm{dv}} = \mathrm{Exp}\left(\frac{-x_{\mathrm{min}}}{\Delta x_{\mathrm{lab}}}\right) - \mathrm{Exp}\left(\frac{-x_{\mathrm{max}}}{\Delta x_{\mathrm{lab}}}\right) \, .$$

- We consider displacements bigger than 200μm.

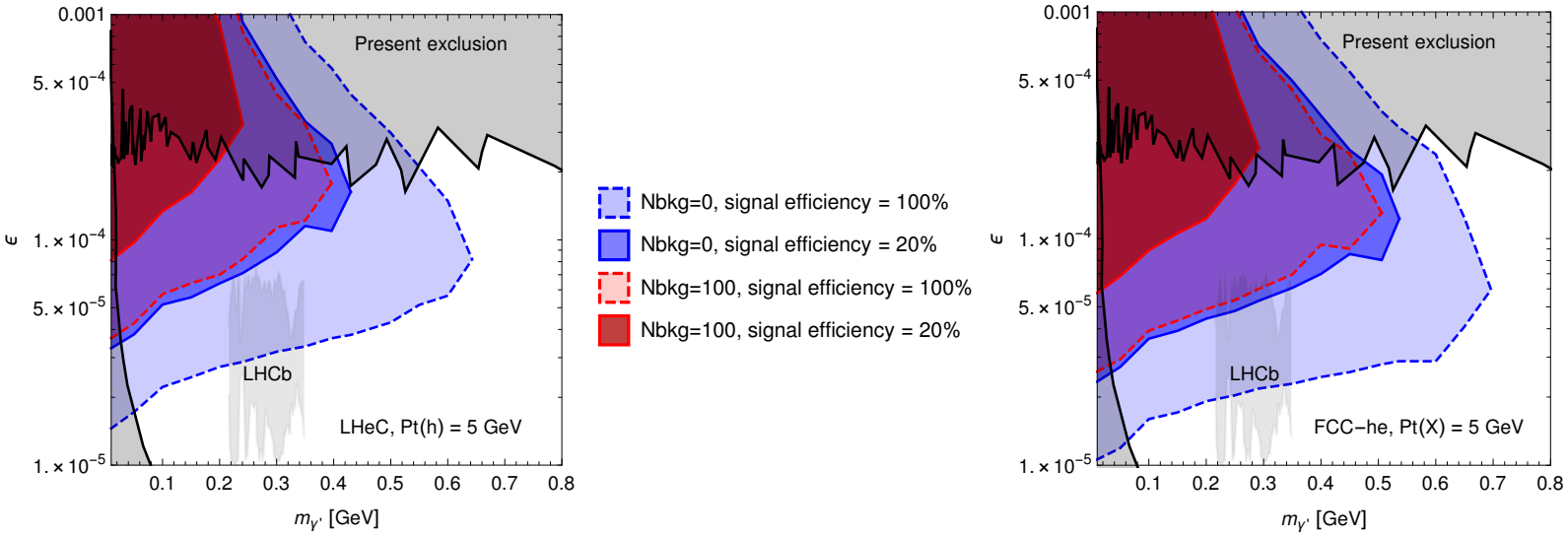
Expected signal events



First look at possible backgrounds

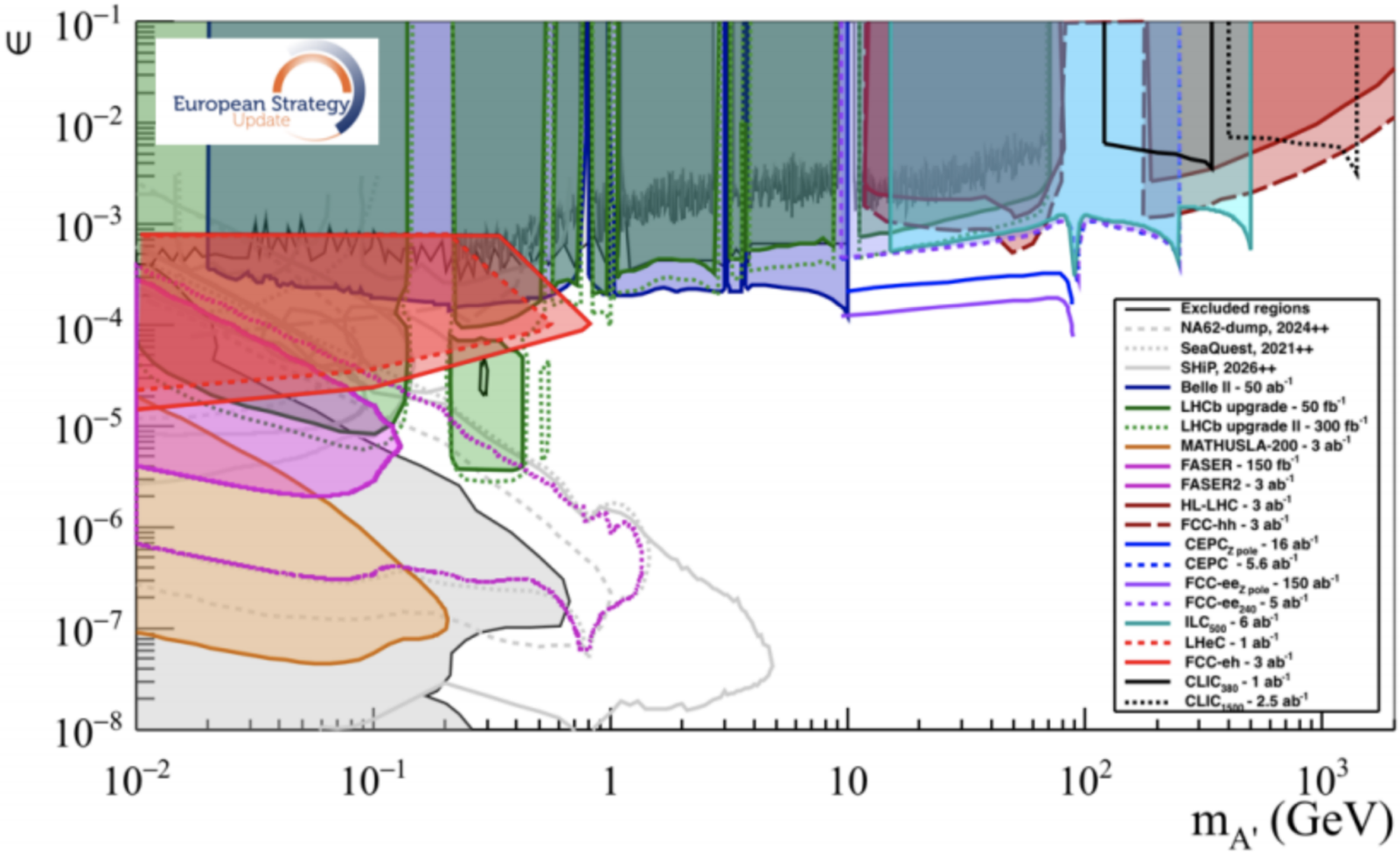
- Most important for dark photon masses below muon production threshold.
- Low-energy photons from $e^- p \to e^- X \gamma$, interacting with the detector material or the beam pipe.
  $\Rightarrow$ Secondary vertex coincides with known material.
- Long-lived mesons (K_S, K_L, and Λ).
  - lifetimes $\mathcal{O}(10)$ cm and longer,
  - expected to be aligned with the proton beam,
  - primary decay channels very different and masses are well known.
- Others (e.g. Cosmics or other machine related backgrounds).
- We consider four scenarios:
  - $N_{\mathrm{bgk}} = 1, 100$ with flat distribution.
  - signal efficiency $= 20\%, 100\%$.
  - Everything for 90% confidence level.

Projected sensitivity of dark photon searches

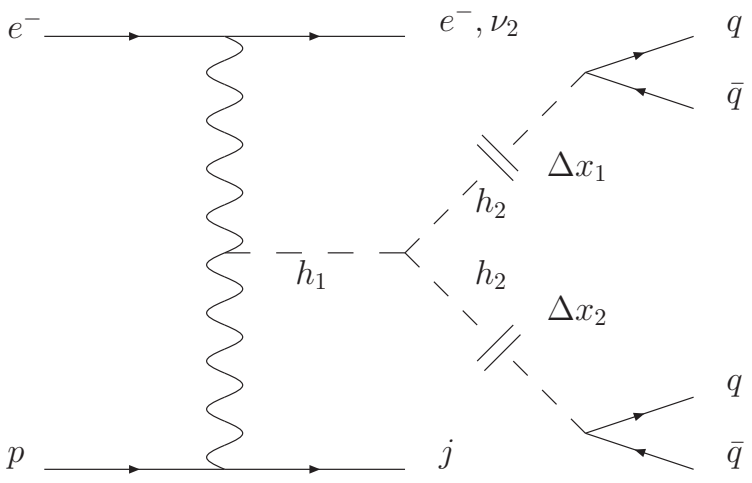


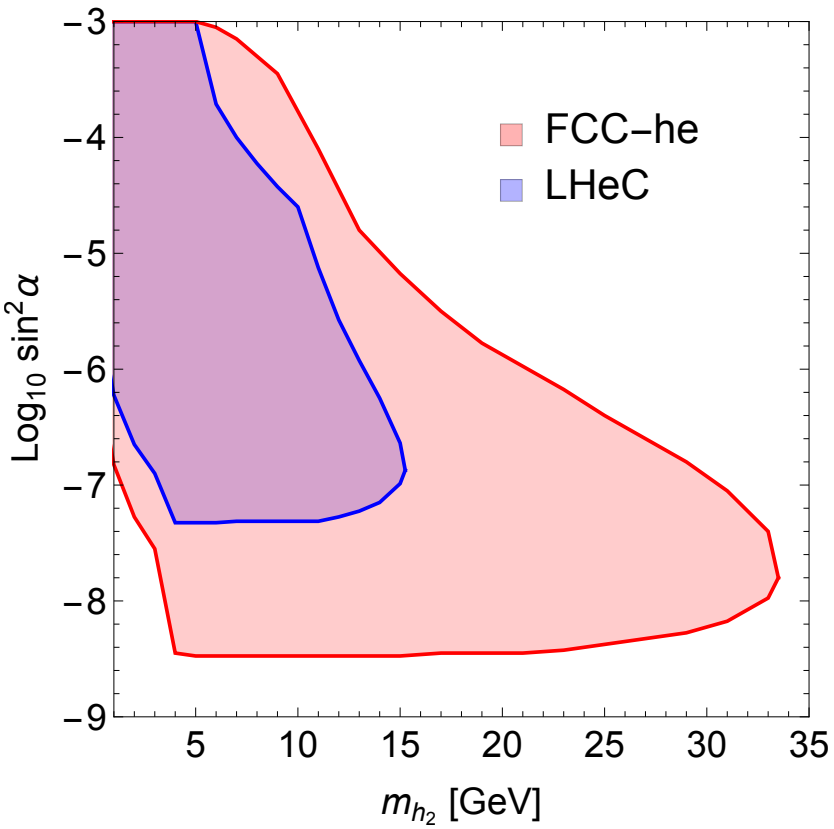
- Present exclusion,
  - lower left corner: E141, E774, Orsay, and NuCal;
  - upper limit: NA48 and BaBar.
- LHCb searches for long-lived particles.
- Preliminary results were created for the European strategy.

From the European Strategy



Detour: exotic Higgs decays to scalar LLPs





- First look at the parton level, input for ESPP update.
- Assumption: background free and 100% signal efficiency.
- Work in progress with J. Zurita.

Conclusions

- Dark photons are part of many BSM sectors.
- They are searched for by many experiments.
- LHC searches are limited by di-muon threshold.
- Electron-proton colliders surprisingly good probe for "light" dark photons.
- Signature relies on lifetimes (around mm), tracking resolution, absence of pile up and low number of backgrounds.
- There are additional production channels worth studying.